Herringbone Approach Procedures for Aircraft: Benefits and Limitations

Introduction and Executive Summary

A common consequence of GPS-based aircraft management systems (e.g., NextGen) is that, even at considerable distance from the airport, each plane flies over the same narrow residential route ("sacrificial" noise corridor) causing concentrated, repetitious, and annoying noise events on the ground under the route[1]. The precision of GPS replaces the formerly imprecise radar-based approaches that spread the overflights over a wider geographic footprint. We know that in many of the new NextGen metroplex designs, the old dispersal patterns resulted in more manageable noise impact, and that the new concentrated NextGen patterns have caused very significant numbers of complaints[2].

The (implicit) FAA argument for advocating such narrow paths is that, in a bigger picture, according to their calculations, there are fewer people on the ground affected by the noise — no matter how intense, damaging, and annoying that concentrated noise may be.[3]

What is missing from this assessment is (a) is it really true that fewer people are annoyed?, and (b) *how much* noise is each annoyed person exposed to? In the old dispersed arrival case, we may have 100 people annoyed, but they are spread over a larger area and are only exposed to a fraction of the total noise. In the NextGen case, we may still have a similar number of people annoyed, but because of the narrow flight corridor, they are exposed to the entire noise burden and, hence, more people per area are affected.

An obvious way to think about mitigating the concentration problem, even with GPS guidance, is to intentionally disperse the routes and have aircraft fly over slightly different paths on approach so that the noise is spread more widely and more equitably over surrounding neighborhoods.[4] Clearly there are many ways to disperse overflights, from random path choices made jointly by Air Traffic Control and the pilot, to a more structured set of subroutes, e.g., a "herringbone" pattern, with some way to alternate selection of subroute from aircraft to aircraft.

This paper explores the dispersion versus concentration trade-off analytically. Figure 1 shows a typical "herringbone" approach scheme, in which a series of parallel subroutes feed into the final approach path to the airport and over which arriving aircraft can be dispersed.

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1 See for example: (a) Hemm R, Stouffer V, et al., *NextGen for Airports, Volume 3: Resources for Airports*, Airport Cooperative Research Program; Transportation Research Board, National Academies Press, 2016 (see this link);
(b) *FAA Facts: Southern California Metroplex*, 2015 (see this link);
(c) Maurice, L, *Implications of Environmental Requirements for NextGen*, FAA presentation to the NAS Transportation Research Board Annual Meeting, January 12, 2010 (see this link).

2 For example, in Palo Alto, CA, where the NextGen SERFR route has concentrated many aircraft approaches to San Francisco, on the order of 50-60 thousand complaints are submitted each month.

3 See for example, (a) Optimization of Airspace & Procedures in the Metroplex (OAPM) documents: Full set of documents at this link;
(b) Aircraft Noise Technical Report at this link; and
(c) Shull M, FAA NextGen and the 2012 to 2015 *"Optimization of Metroplex Airspace"*, January 30, 2016 (see this link). See Chapter VII, *Sacrificial Noise Corridors Enable the "Net Noise Reduction" Measurement Technique*, in particular.

4 See for example, Aviation Environment Federation, *Approach Noise at Heathrow: Concentrating the Problem*, Heathrow Association for the Control of Aircraft Noise (HACAN), March 2010 (see this link).

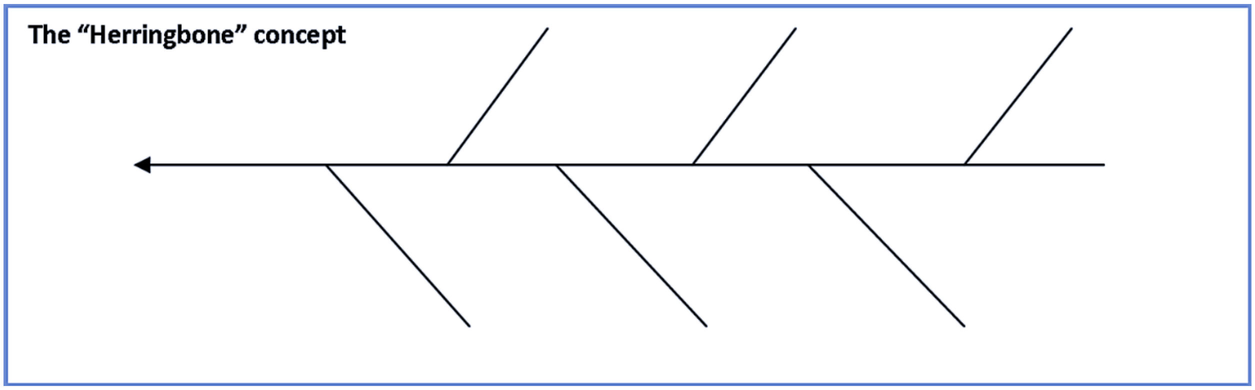

Figure 1: Schematic "herringbone" approach concept that disperses arrivals from above and below the straight leg approach with different merging points. Aircraft arrive in a sequence to ensure that minimum separation distances are maintained. (AEF/HACAN report)

In the context of such a simple herringbone approach model, the analysis we present in this paper shows that the argument for concentration as opposed to dispersion is fallacious:

1. The noise exposure level profiles per subroute for herringbone configurations are significantly lower than for a single approach corridor. The "achievable" and the maximum noise attenuation possible with various herringbone configurations change roughly as 1/N, where N is the number of subroutes and assuming the traffic is divided evenly between subroutes.
2. Estimates of the total number of people annoyed by noise under various herringbone configurations are complex, but not significantly different compared to the number annoyed with a single corridor.
3. More important than the total number of people annoyed under various herringbone configurations, the *average level of noise exposure per person annoyed* is significantly less.
4. The mechanism for noise reduction with herringbones is dispersion. In directing aircraft over different approach subroutes, parameters like the approach altitude and flight characteristics are not changed. Thus, the peak noise levels per overflight event remain the same, with or without the herringbone, but the *number of such events* at a given location decreases by 1/N.
5. Implementation of herringbone approaches does require more ground area and a mechanism for air traffic controllers to apportion aircraft among the subroute structure. The ground area required for herringbones is not significantly different from that used in pre-NextGen patterns for approaching aircraft over poorly localized routes. Given this long-standing prior experience, it should not be a difficult technical or operational problem to accommodate the use of herringbone approach patterns.

The essential point is that herringbones can be very helpful in making local noise exposure more tolerable. They are not panaceas though in the sense that the noise level per overflight event is not reduced. Rather the aggregate overflight noise is dispersed so that annoyance at a given ground location is reduced. Thus, herringbones contribute significantly to noise reduction, but do not substitute for intrinsic noise reduction methods such as flying as high as possible, flying as quietly as possible, and flying as much as possible over unpopulated areas.

Background and Approach

An analysis of herringbone approach patterns poses many questions, such as:

- How many subroutes are needed to disperse noise adequately?
- How far apart should the subroutes be so they don't cross-feed noise to each other?
- How effectively is the noise reduced with various subroute patterns?
- How many people are affected by noise under alternative subroute arrangements and how severe is the average noise exposure per affected person?
- How big a ground footprint does the herringbone occupy?

The analysis in this paper is intended to illuminate these questions[5]. The crux of the analysis we will describe is straightforward:

1. if we spread the aircraft subroutes out geographically, we can compute noise profiles (DNL[6] in FAA terms) as a function of the base DNL level for a concentrated route, the number of subroutes, the distance between subroutes, and the observer distance from each subroute.
2. Given a DNL profile, we can compute the number of annoyed residents per area at each point in the profile using an appropriate dose-response curve, i.e., a mapping of DNL level to the percentage of people annoyed.

The results of these calculations will allow us to compute various integrated statistics about the effects of a given herringbone configuration, including:

1. The "achievable" and the maximum theoretical noise attenuation possible with various herringbone configurations, as compared with the single corridor noise level.
2. Estimates of the number of people annoyed by noise under the single corridor and various herringbone configurations, and the average amount of noise they are exposed to.
3. An explanation of how the total number of annoyed residents below the combined subroute pattern changes depending on (a) the base DNL level of the single route path, (b) the geometry of the herringbone arrangement, and (c) the shape of the dose-response curve used.
4. An estimate of the ground area required to achieve meaningful dispersal of noise.

Figure 2 shows an idealized sketch of a herringbone approach pattern that we will use for our analysis.

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[5] There are a few other analyses of herringbone patterns, or Equivalent Lateral Spacing Operations (ELSO). See for example, Brenner M, Brooks C, and Hansman RJ, *Impacts of Aircraft Flight Track Dispersion on Airport Noise*, MIT International Center for Air Transportation, April 21, 2016 (at this link). The Brenner et al. analysis only calculates dispersion effects on DNL but does not calculate number of persons affected or average noise exposure per person as a function of subroute separation.

[6] The Day-Night Average Sound Level (L_{dn} or DNL) is the logarithm of the average noise energy level over a 24-hour period expressed in decibels (dB). The noise between the hours of 10pm and 7am is artificially increased by 10 dB (a factor of 10) to take into account the typical decrease in community background noise of ~10 dB during this period.

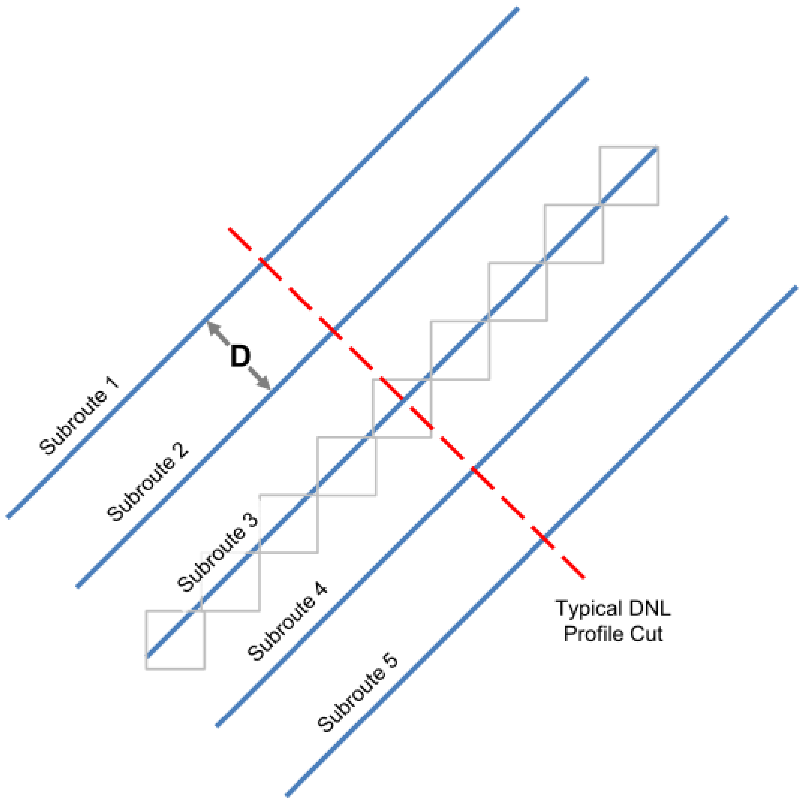

Figure 2: Sketch of the "herringbone" approach pattern to be analyzed with variable numbers of subroutes, denoted as N, and variable distances between subroutes, denoted as **D**.

A Few Notes about the Peak Model and How Calculations will be Done

The calculations and results presented here use an analytical formulation developed in a separate aircraft noise peak modeling paper[7]. In that paper, we computed the profile of an aircraft overflight noise peak based on the geometry of the overflight and the simple physics of sound propagation (see Figure 3**Error! Reference source not found.**a). We assumed that an aircraft is flying relative to an observer in a straight path with constant velocity and altitude. The physics included the (geometric) $\mathbf{1/r^2}$ fall off in intensity with distance, atmospheric attenuation, and Doppler effects from the finite velocity of sound. This first-order model ignored complications of anisotropy (e.g., engines louder in the rear than in front), and refractive and reflective properties of the air between the aircraft and the observer. Examples of fits of this analytical model to real data collected in north Palo Alto are shown in Figure 3b.

It is shown in the paper that a quantity $\mathbf{r_{min}^2} = \mathbf{d^2} + \mathbf{h^2}$ is important in the model, where $\mathbf{r_{min}}$ is the 3-dimensional distance of closest approach of the observer to the aircraft, **d** is the ground distance to the overflight track, and **h** is the aircraft altitude above ground level (AGL). It is further shown that the maximum intensity, $\mathbf{I_{max}}$, of an overflight peak falls off as $\mathbf{1/r_{min}^2}$ but the total energy, **E**, under an overflight peak (precursor to calculating DNL) falls off only as $\mathbf{1/r_{min}}$.

[7] Rindfleisch, TC, *Theoretical Model of Aircraft Overflight Sound Peak Shape*, August 2016; see this link).

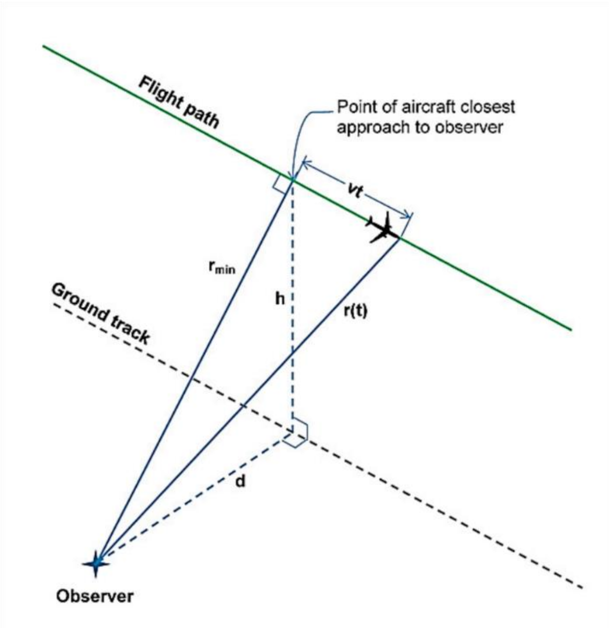

Figure 3a: Diagram of aircraft overflight geometry relative to a ground observer.

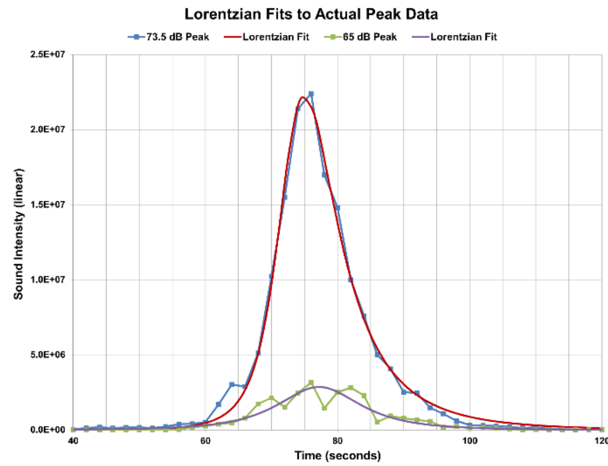

Figure 3b: Examples of model fits to real recorded data — a 73.5 dBA peak (blue line) and a 65 dBA peak (green line).

Figure 3: **(a)** Diagram of aircraft overflight geometry relative to a ground observer and **(b)** examples of fits of the peak model to actual data measured with a sound monitor on August 3, 2015, in north Palo Alto, CA. The measured peaks include a 73.5 dBA overflight peak and a 65 dBA peak.

Since the altitude, **h**, is a constant in the herringbone model we are examining, we can factor it out of the formula for $\mathbf{r}_{\mathbf{min}}^{\mathbf{2}}$, giving $\mathbf{r}_{\mathbf{min}}^{\mathbf{2}} = \mathbf{h}^{\mathbf{2}}\,(\mathbf{d}^{\mathbf{2}}/\mathbf{h}^{\mathbf{2}} + \mathbf{1})$. With this formulation, we speak of dimensionless distance units, **d/h**, in terms of which the observer distance from the flight path is measured. The examples, plots, and discussion that follow generally talk about "distance" in these dimensionless units of the aircraft altitude. Thus, a "distance" of **1** means **d/h = 1** or **d = h** so the observer is at a distance from the flight path equal to the aircraft altitude. If **d/h = 0**, it means the observer is directly under the flight path, and so on.

The explicit value of **h** is only needed to compute actual physical distances, for example, when doing atmospheric attenuation calculations. If the plane flies at 4,000 ft, a **d/h = 1** means the observer is 4,000 feet (or 0.76 statute miles) from the ground track and 5,657 feet (or 1.07 miles) from the aircraft.

Similarly, the distance between herringbone subroutes, **D**, is expressed in **d/h** units. For example, for **D/h = 1**, the subroutes are a distance **h** apart (0.76 miles). For **D/h = 2**, the subroutes are 1.51 miles apart, and so on.

This all may seem strange at first but it makes the mathematical expressions simpler and the plots more general.

Finally, recall that quantities, $\mathbf{Q}_{\mathbf{dB}}$ expressed in logarithmic decibel units (dB), e.g., DNL, come from the underlying quantity, $\mathbf{Q}$, (e.g., weighted average total energy) according to the relation:

$\mathbf{Q}_{\mathbf{dB}} = \mathbf{10}\,\mathbf{log}_{\mathbf{10}}(\mathbf{Q})$, where "$\mathbf{log}_{10}$" means logarithm to the base 10.

Effects of Herringbones on DNL and Annoyance Levels

A Specific Example — Computing DNL Profiles

Using data from a recent set of measurements taken in northern Palo Alto (data were collected between August 5-14, 2016 at a location essentially directly under the SERFR route), the parameters from the raw data source are shown in Table 1:

# Aircraft/Day	325
Energy (SEL) per peak	6.0E+07
DNL (Peaks Only)	53.5 dBA
Aircraft altitude	~4,000 ft
Atmospheric attenuation	0.04 %/ft[8]
House density	3,400 per sq mi

Table 1: Typical overflight noise data from north Palo Alto

As a first step, we use the data collected under the conditions in Table 1 to scale overflight profiles with base DNLs of 50 dBA, 55 dBA, and 60 dBA so we can see the effects of base DNL on the calculations. To illustrate the calculation steps more concretely, we choose a median base DNL of 55 dBA. We break the main approach route and traffic into 2, 3, 4, and 5 subroutes, each with equal parts of the total flight traffic. Using the theoretical peak model mentioned in Footnote 7, we can compute the DNL distribution profile along an axis perpendicular to the herringbone subroutes (see Figure 2).

Figure 4a-d below show the results of these calculations. The Figure is made up of four subplots of DNL profiles, showing net DNL as a function of distance from the center of the herringbone flight path (in d/h units). Each color represents a different inter-subroute distance, **D** (in **d/h** units), from 0 to 3.

For each subfigure, the dark blue plot (**D = 0h**) is identical and represents the case in which all aircraft fly directly overhead – essentially the way the SERFR route operates since the implementation of NextGen. As the distance, **d/h**, increases from the ground track, the observed DNL values in the dark blue plot drop off as $\mathbf{log_{10}}\,[\mathbf{1}/\sqrt{\mathbf{1} + (\mathbf{d}/\mathbf{h})^{\mathbf{2}}}]$. If we take 45 dBA as a typical background noise level[9], we note that the central dark blue curve merges into the background (i.e., reaches 45 dBA) at a distance of about 1.8 d/h units from the ground track (~1.4 miles for h = 4,000 ft).

The DNL profile plots for herringbones with inter-subroute distances, **D/h**, greater than 0 are calculated by adding up the intensities (energies) received at a given point along the profile from each of the subroutes[10] and then converting the net energy into logarithmic DNL units. As can be seen in these figures, for an inter-subroute distance between 0 and 1 the DNL profile is basically a single (broadening) peak. At inter-subroute distances greater than 2, the individual subroute peaks in each profile become increasingly apparent as the crossover effects between subroutes decrease.

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[8] See for example, Russell, DA, *Acoustics and Vibration Animations*, Graduate Program in Acoustics, Pennsylvania State University, 2016 (see this link). The intensity attenuation coefficient used is equivalent to 0.57 dB/100m at 25°C, 50% humidity, 1 atm, and 1000 Hz.

[9] At the Palo Alto measurement site, the average background DNL (no aircraft present) was 47.4 dBA.

[10] Computing net energy contributions from the various subroutes includes not only spherical wave expansion effects, but also atmospheric attenuation effects.

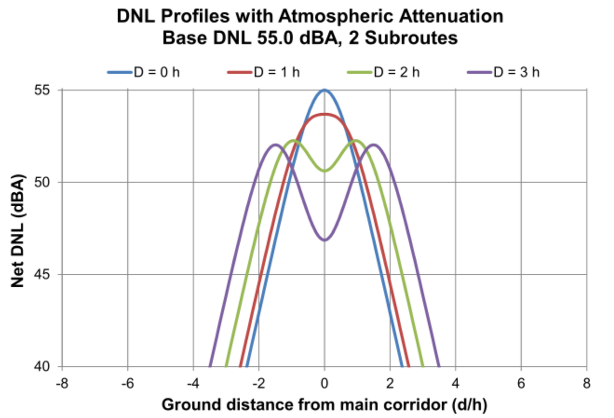

Figure 4a: Two subroutes

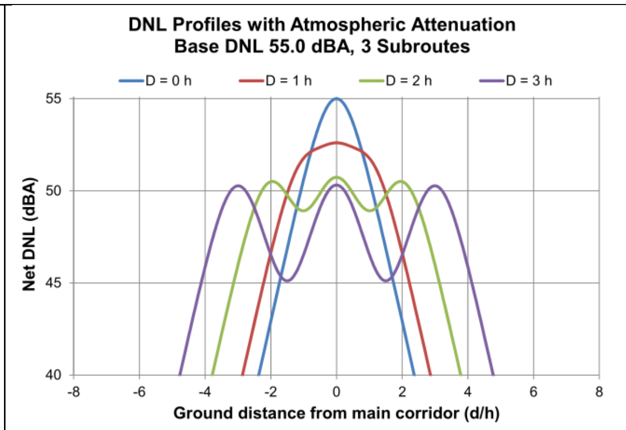

Figure 4b: Three subroutes

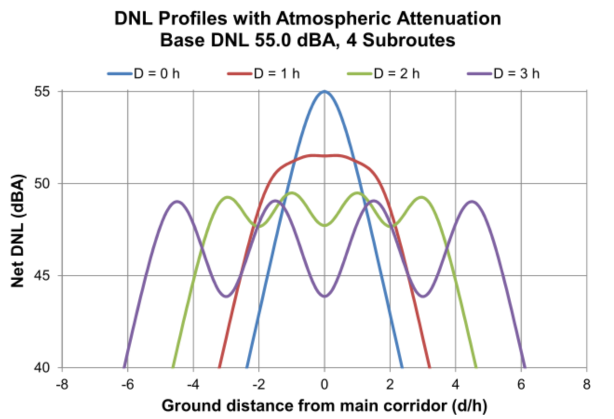

Figure 4c: Four subroutes

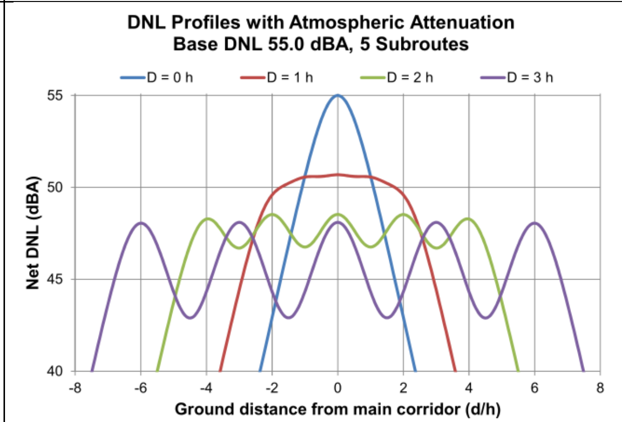

Figure 4d: Five subroutes

Figure 4a-d: DNL profiles for 2, 3, 4, and 5 subroutes using 55 dBA base DNL overflight data.

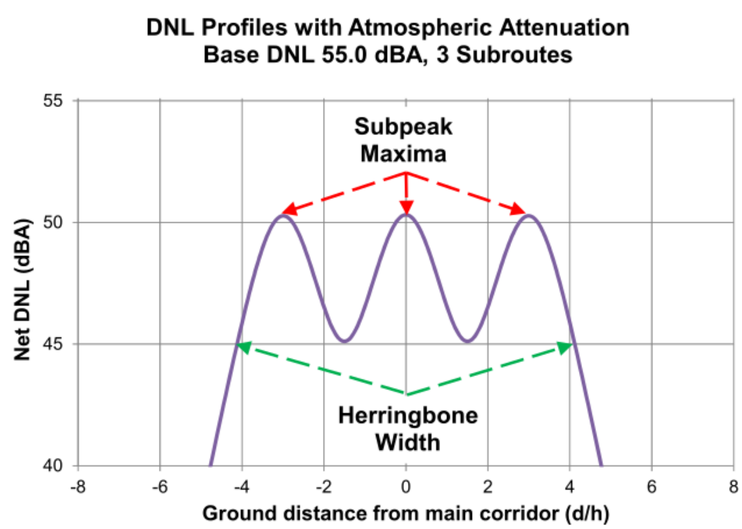

Figure 5: Illustration of useful DNL profile features: (1) the set of subpeak maxima for which the average value will be used, and (2) the total geographic width of the herringbone route set for DNL values above 45 dBA.

A Specific Example — Analyzing the DNL Profiles

In this section, we will look at ways to compare herringbone route patterns for the 55 dBA example data set — as a function of the number of subroutes and as a function of the distance separating subroutes.

In preparation for this discussion, we introduce two useful features that will be extracted from each DNL profile: (1) the set of subpeak maxima and (2) the total geographic width of the herringbone pattern for DNL values above an ambient background level of 45 dBA. These features are illustrated in Figure 5 above.

First, for each subroute configuration, we plot the average DNL value of the subroute profile peak maxima as a function of the inter-subroute separation, **D/h** (see Figure 6). In this plot, we see that for **D/h >~ 2**, the benefits of increasing the subroute separation essentially disappear.

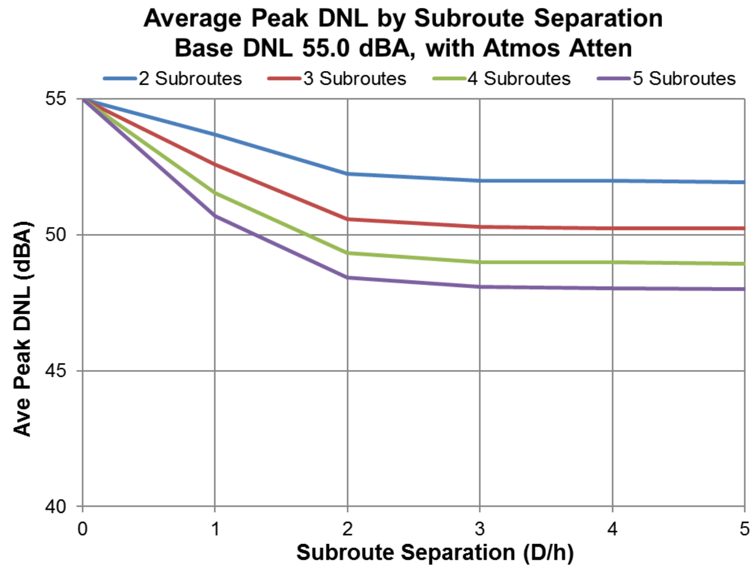

Figure 6: The average subpeak DNL for various numbers of subroutes as a function of subroute separation

So, for the purposes of this analysis, we will consider a subroute separation of **D/h ~ 2** to be nearly optimal. At (or above) this separation, any additional benefit must come from using more subroutes (~1/N). This effect of this approximation is shown in Figure 7.

The lesson from this analysis is that to fit multiple herringbone subroutes into a relatively constrained space one does not lose the noise mitigation advantage (in terms of reduced DNL values) by using relatively small inter-subroute separation distances. The penalty at **D/h = 2** ranges from ~0.3 dB with 2 subroutes to ~0.4 dB with 5 subroutes.

A Specific Example — Computing the Effects of a Herringbone on the Number of People Annoyed

Given the DNL profiles for various herringbone subroute configurations and a base DNL of 55 dBA, we can now calculate the number of people annoyed under each subroute configuration and the amount of noise they are exposed to. To do this, we must convert DNL values at each point in a profile into the probability of annoyance[11]. Then given the density of people under the profile, we multiply the probability of annoyance at each point by the people density and sum

[11] We only consider DNL values above the ambient 45 dBA background level mentioned in Footnote 9.

these over the entire profile to get a total. Such a mapping of noise level to percent annoyed is called a *dose-response* curve.

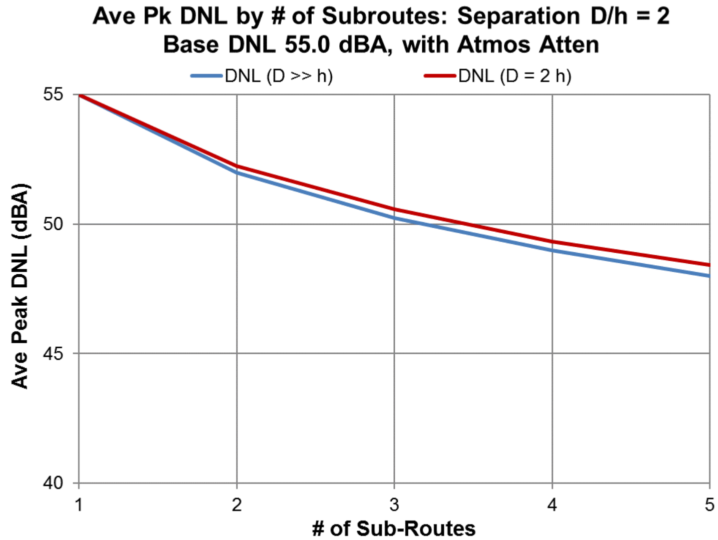

Figure 7: The red curve shows the DNL reduction obtained as a function of the number of subroutes for a separation of D/h = 2. The blue curve shows the greatest DNL reduction possible for the various subroute configurations (1/N), assuming they are very widely separated.

A detailed discussion of past efforts to collect survey data on annoyance as a function of noise level (DNL) can be found in Appendix A (page 21). To summarize that discussion, there are two dose-response curves that we will use to assess the range of ground impact of herringbone patterns (see Figure 8).

The first, used by the FAA basically unchanged since 1979, is called the *Schultz/USAF* curve. It is highly permissive in that it approximates the lowest bound of accumulated annoyance survey data (see Figure 15). As a result, it predicts a very small number of people will be annoyed at noise levels seen in residential areas away from the final landing approaches around airports (50-60 dBA). It also very insensitive to annoyance variations as a function of DNL value in this range.

The second dose-response relation we call the *Miedema* curve, after the research team that first derived it.[12] This curve approximates the median of the accumulated annoyance survey data up to 2000. Even though the Miedema curve predicts that significantly more people will be annoyed at a given DNL level, it still is relatively permissive. For example, it predicts that only 25% of people exposed to a 65-dBA noise level (DNL) will find it highly annoying. As a simplified example, such a DNL value corresponds to a 75-dB (peak intensity) overflight event every 3-4 minutes during the entire 18-hour waking day (using overflight parameters like those in Table 1)!

The next step in our analysis of the number of people annoyed uses the subroute DNL profiles (see Figure 4) and the two dose-response curves (see Figure 8) to convert the DNL profiles to estimated profiles of the number of people annoyed as a function of ground distance from the main overflight corridor.

[12] As indicated in Footnote 23, later work by Fidell et al has arrived at a very similar dose-response curve from the accumulated annoyance data sets. We use the label *Miedema* simply as a shortcut.

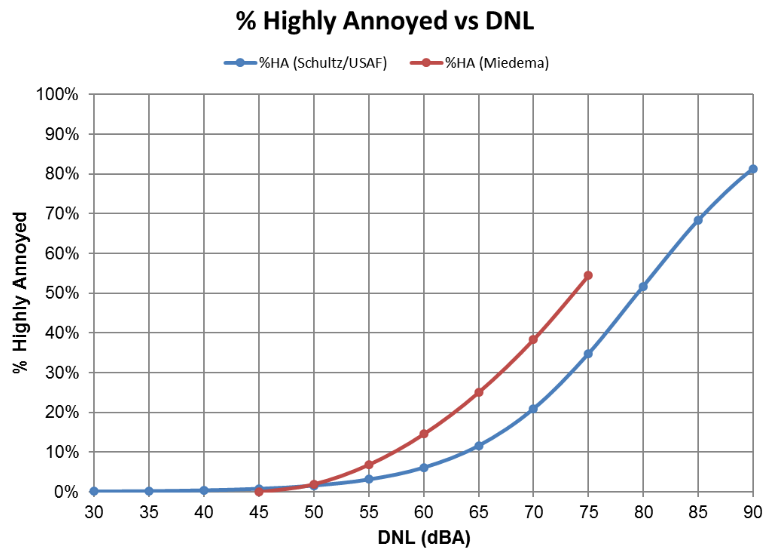

Figure 8: Dose-response curves approximating the lower bound (Schultz/USAF curve) and median (Miedema curve) of cumulative survey data on noise annoyance.

To make this more concrete, we show the computed the profiles for the previous 55 dBA Palo Alto example using a 3-subroute herringbone and inter-subroute spacings of **D/h = 0, 1, and 2** (see Figure 9). Note that we have changed the horizontal and vertical axis scales on the plots to make the details of the profile curves easier to see, and we have imposed a lower limit of DNL 45 dB for any noise impact — noise below that DNL level is assumed to be masked by ambient background noise.

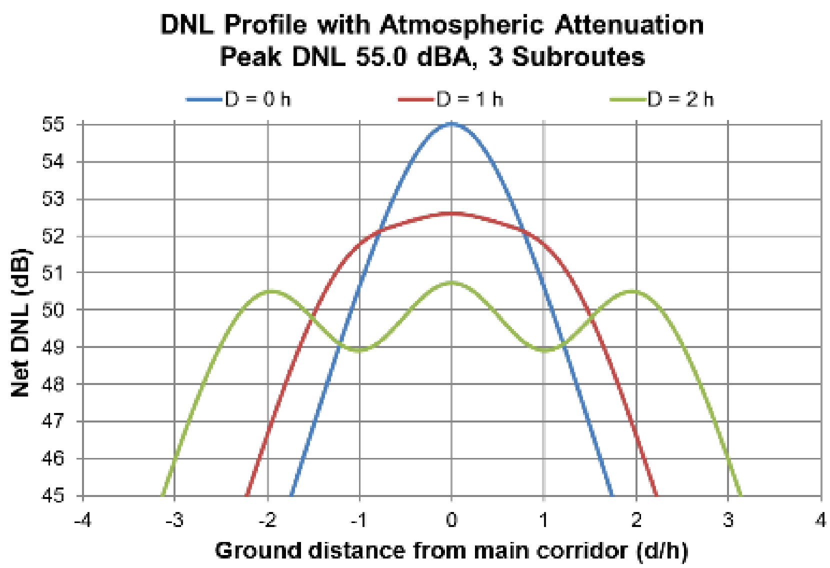

Figure 9a: DNL profiles vs subroute separation

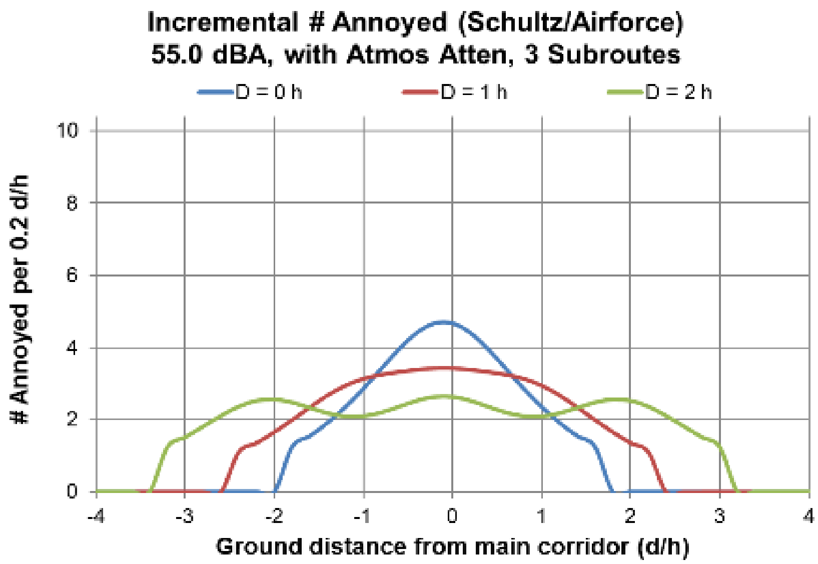

Figure 9b: # annoyed profiles with Schultz/USAF dose-response

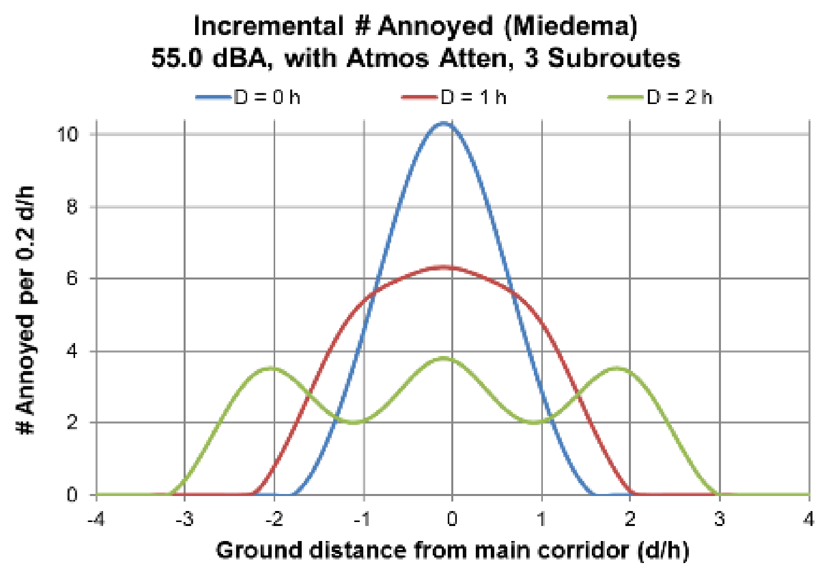

Figure 9c: # annoyed profiles with Miedema dose-response

Figure 9: **(a):** DNL distribution profile as a function of subroute separation; **(b):** "# annoyed" profile for the Schultz/USAF dose-response curve; **(c):** "# annoyed" profile for the Miedema dose-response curve. The profiles shown in Figure 9b and Figure 9c correspond to the incremental number annoyed in 0.2 d/h wide swaths along the profile and one mile long in the direction of a subroute, assuming a 1,000 person per square mile population density.

The qualitative differences between the effects of the two dose-response curves (Figure 8) can been seen in the plots in Figure 9b and Figure 9c. The Schultz/USAF curve is lower (fewer people annoyed at a given DNL) and flatter in the DNL range 45-55 dB of Figure 9a. As a result, the total number annoyed profile (Figure 9b) is lower and has smaller differences with increasing subroute separations. Conversely, the Miedema dose-response curve is higher (more people annoyed) and has a greater slope with increasing DNL. Thus, the total number annoyed profile (Figure 9c) is higher and has greater differences between successive subroute separations.

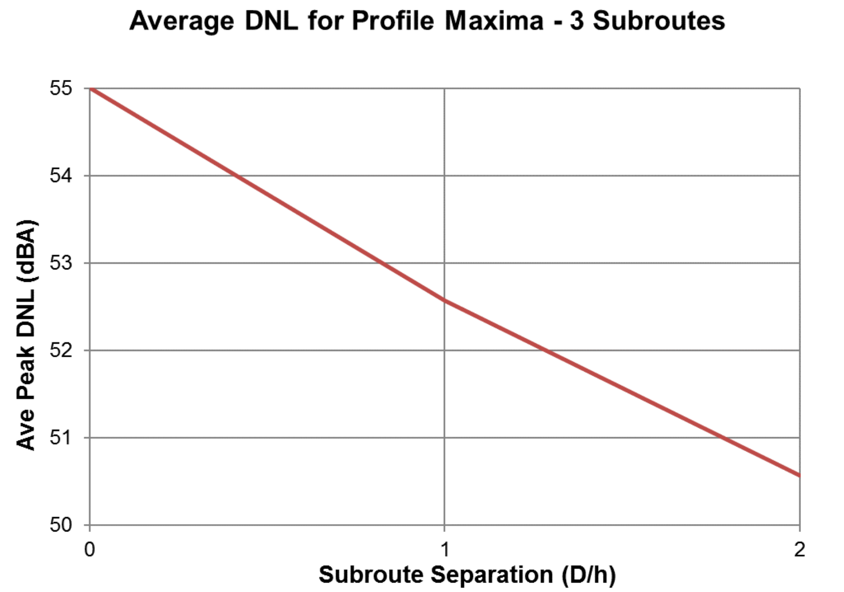

Figure 10a: Mean profile maxima DNL

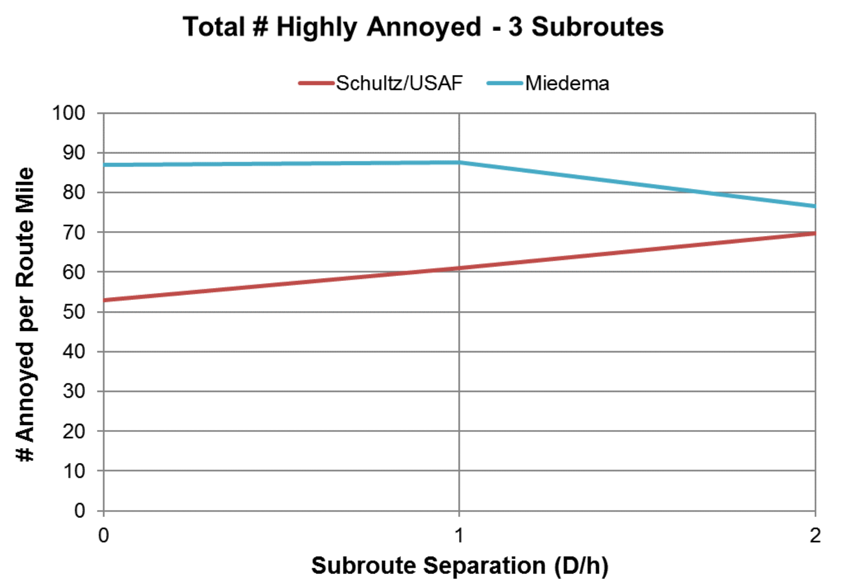

Figure 10b: Total # Annoyed

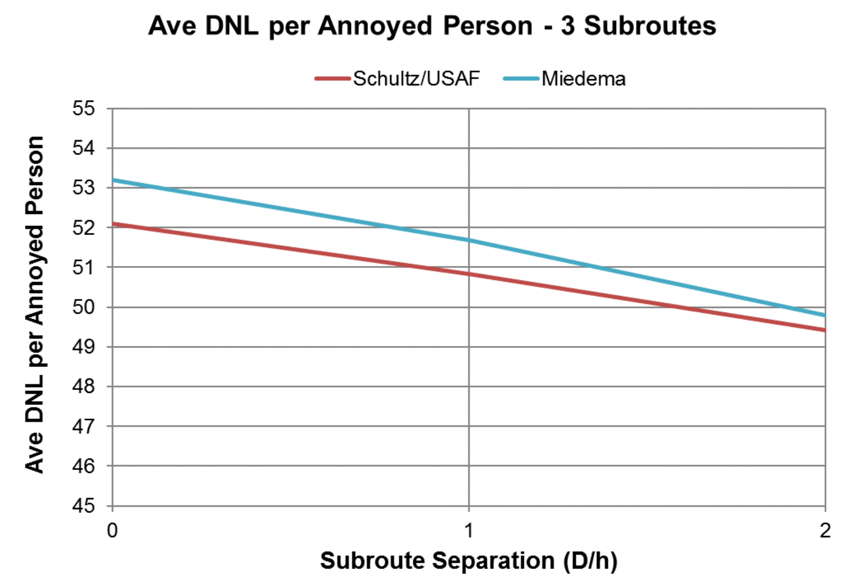

Figure 10c: Ave DNL per Person Annoyed

Figure 10: **(a**) Average DNL for profile maxima; **(b**) Total # annoyed for the Schultz/USAF and Miedema dose-response curves; **(c)** Average DNL per annoyed person under the Schultz/USAF and Miedema dose-response curves.

Finally, when we add up all the annoyed people over the dispersed routes, we ask: (a) how do those totals compare to the number annoyed along a single concentrated route, and (b) what are the average noise levels each annoyed person is exposed to for various subroute configurations? These questions are answered in Figure 10.

Several things stand out in these calculations, even though we have only looked at 55 dBA data set. In Figure 10a, the average DNL values for subroute profile maxima decrease from 55.0 dBA (D/h = 0) to 50.7 dBA (D/h = 2). This 4.3 dBA reduction is almost equal to the 4.8 dBA reduction resulting simply from the physical 1/N factor from having 3 subroutes.

In Figure 10b, the total number of persons annoyed[13] under the Schultz/USAF dose-response curve (red line) is least with zero subroute separation, i.e., the single concentrated corridor case the FAA advocates. As the subroute separation increases to D = 2h, the number of people annoyed *increases* by 32% from 52.9 to 69.8 people per subroute mile.

In Figure 10b, the number of people annoyed under the Miedema dose-response curve (blue line) is highest with zero subroute separation, and *decreases* with subroute separation. We expect that with the Miedema curve there will be a higher number of people annoyed than under the Schultz/USAF curve because the Miedema curve conforms to the median of the annoyance data sets and explicitly captures the fact that there are more people annoyed by a given DNL level.

In contrast to the Schultz/USAF case though, the *total number of people annoyed* under the Miedema curve *decreases* as the subroute separation increases from D = 0h to 2h — from 86.9 to 76.5 people per subroute mile (12%). Thus, the argument for concentrating aircraft approach patterns over a single narrow route versus dispersing the pattern using herringbone subroutes depends heavily on which dose-response curve is used. We would argue that the

[13] Per subroute mile per 1,000 people per square mile.

Miedema/Fidell curve is a much more reasonable representation of the accumulated annoyance research data as explained in Appendix A.

Finally, in Figure 10c we see that the average noise exposure (DNL) per person annoyed under these two dose-response curves[14] decreases as a function of subroute separation. This is important because the main goal of dispersing noise is to minimize the ground noise disturbance from overflights. The reduction in the average DNL per person annoyed as the subroute separation increases from the D = 0h to 2h is: (red line) 2.7 dBA for the Schultz/USAF curve (52.1 to 49.4 dBA), and (blue line) 3.4 dBA for the Miedema curve (53.2 to 49.8 dBA).

This additional metric, not even considered by the FAA, is telling. Even with the varied results of the total number annoyed above, the fact that herringbone patterns greatly reduce the noise experienced per annoyed person *for both dose-response curves* can be strongly argued to be a much more reasonable and humane way of assessing and minimizing the impact of overflight noise patterns.

Generalizing These Calculations to Compare the Performance of Herringbone Configurations between 50 and 60 dBA

In this section, we show the results of applying calculations analogous to those above for the 55 dBA base DNL example to data for additional base DNLs of 50 and 60 dBA. The results for these three base DNL values allow us to see more clearly how herringbone approach patterns behave under a broader set of conditions. The calculations were done for herringbones with 2 to 4 subroutes and with separations from D = 0h to 5h. As before, 45 dBA is used as the lower limit for aircraft noise to have any effect above background. The results of these calculations are shown in Figure 11 - Figure 13.

For each base DNL, a multipart figure shows, **(a)** the average DNL values for subroute profile maxima; **(b)** and **(c)** the total number of people annoyed under the Schultz/USAF and Miedema dose-response curves; and **(d)** and **(e)** the average DNL per person annoyed for both dose-response models.

As will be seen, the data about herringbone pattern performance presented in these Figures are somewhat complex. There are important interactions between herringbone configuration parameters, including the base DNL of the traffic being dispersed; the number of subroutes used; the subroute separation; the shape of the dose-response relationships between noise level (DNL) and percentage of people annoyed; and the performance metrics being used (i.e., the total number of people annoyed and the average DNL affecting each person annoyed).

The figures are shown sequentially below. The plots for all three figures have the same axis scaling so that the relative values of the various computed entities can be compared more easily. We will offer summary discussion and conclusion comments following Figure 13…

[14] The average DNL per person annoyed is calculated, for each subroute separation, as the dot product of the DNL profile in Figure 9a with the corresponding dose-response profile in Figure 9b and c, divided by the appropriate total number annoyed in Figure 10b.

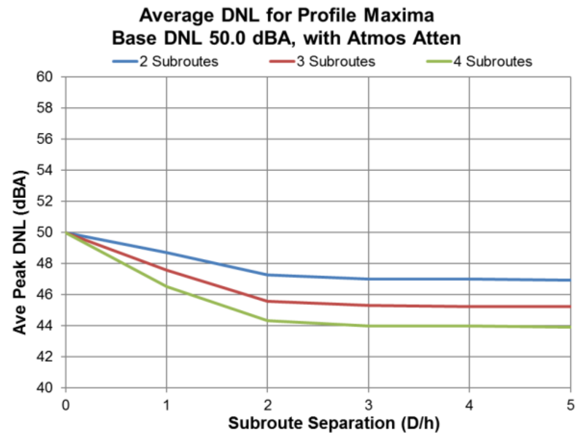

Figure 11a: Average DNL of profile maxima

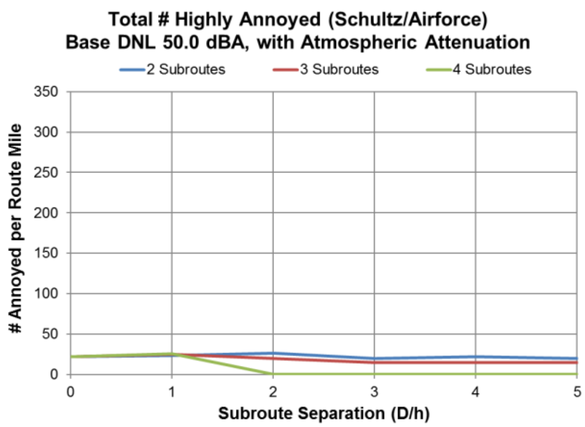

Figure 11b: # Annoyed (Schultz/USAF)

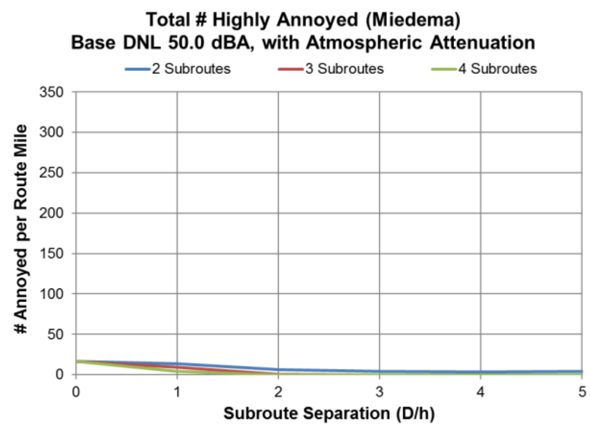

Figure 11c: # Annoyed (Miedema)

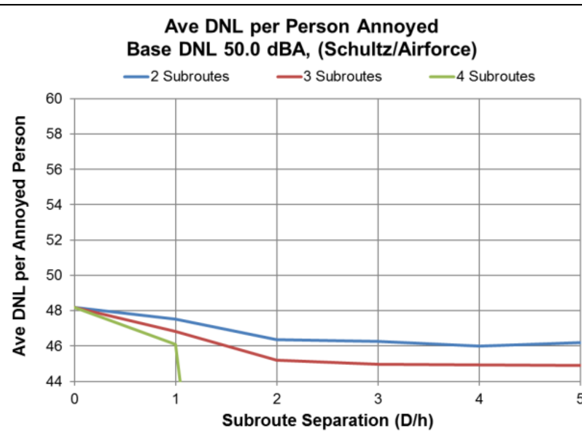

Figure 11d: Average DNL per Person Annoyed (Schultz/USAF)

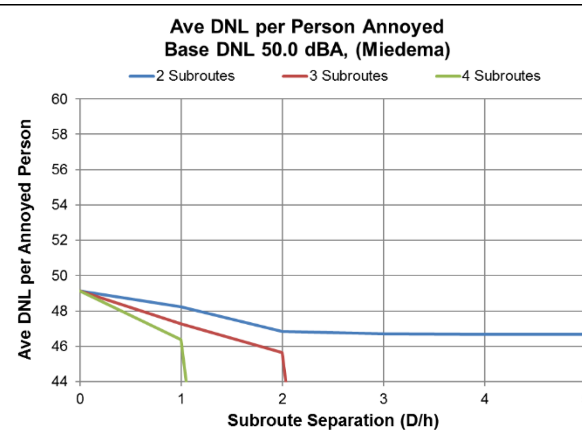

Figure 11e: Average DNL per Person Annoyed (Miedema)

Figure 11: Base DNL 50 dBA — **(a**) Average DNL of profile maxima; **(b**) Total # annoyed (Schultz/USAF); **(c)** Total # annoyed (Miedema); **(d)** Average DNL per person annoyed (Schultz/USAF); **(e)** Average DNL per person annoyed (Miedema).

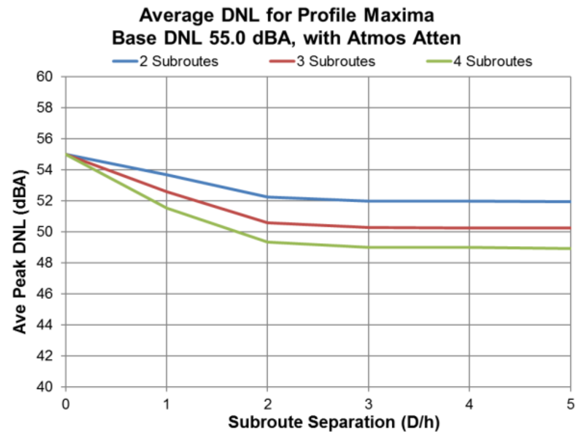

Figure 12a: Average DNL of profile maxima

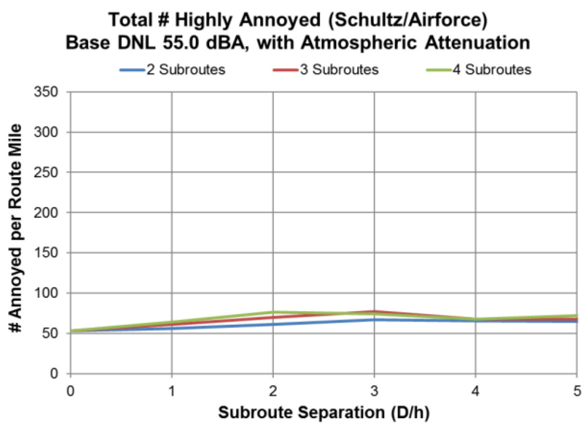

Figure 12b: Total # Annoyed (Schultz/USAF)

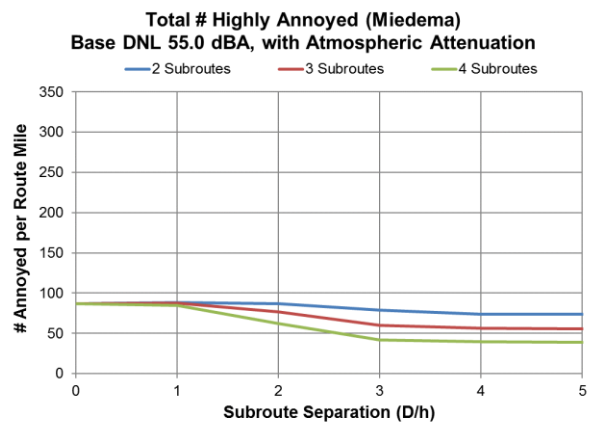

Figure 12c: Total # Annoyed (Miedema)

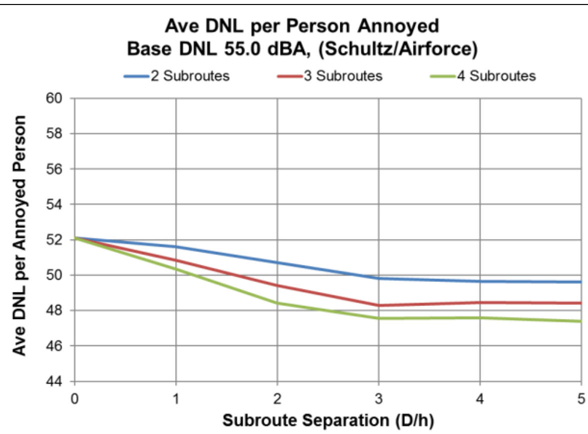

Figure 12d: Average DNL per Person Annoyed (Schultz/USAF)

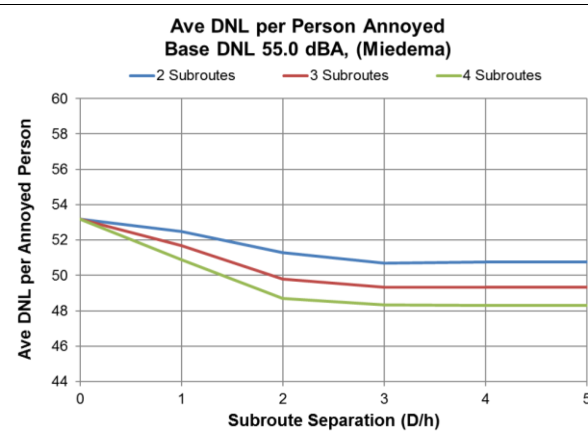

Figure 12e: Average DNL per Person Annoyed (Miedema)

Figure 12: Base DNL 55 dBA — **(a**) Average DNL of profile maxima; **(b**) Total # annoyed (Schultz/USAF); **(c)** Total # annoyed (Miedema); **(d)** Average DNL per person annoyed (Schultz/USAF); **(e)** Average DNL per person annoyed (Miedema).

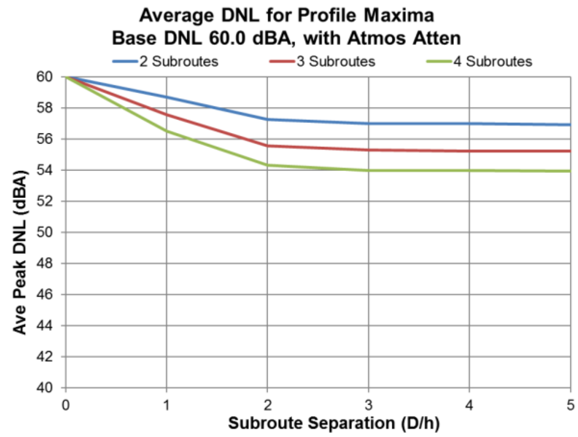

Figure 13a: Average DNL of profile maxima

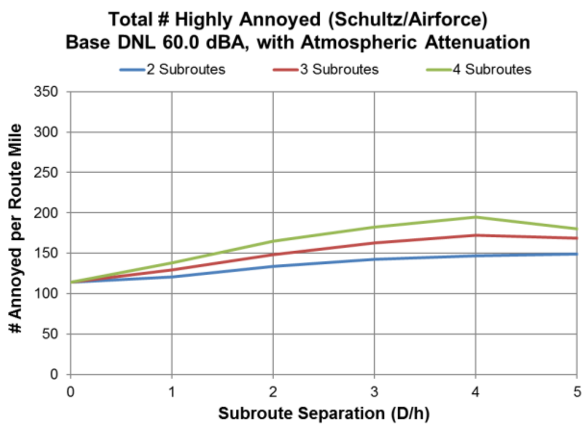

Figure 13b: # Annoyed (Schultz/USAF)

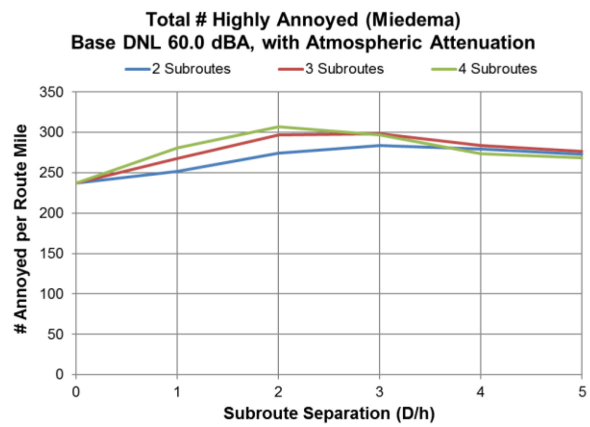

Figure 13c: # Annoyed (Miedema)

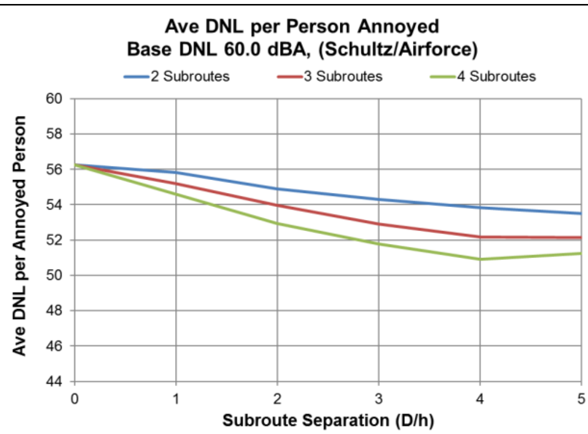

Figure 13d: Average DNL per Person Annoyed (Schultz/USAF)

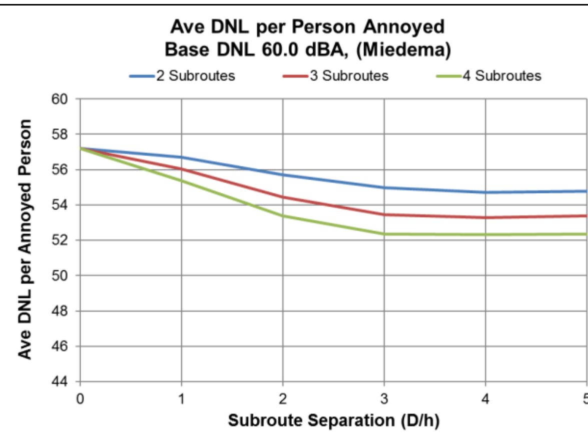

Figure 13e: Average DNL per Person Annoyed (Miedema)

Figure 13: Base DNL 60 dBA — **(a**) Average DNL of profile maxima; **(b**) Total # annoyed (Schultz/USAF); **(c)** Total # annoyed (Miedema); **(d)** Average DNL per person annoyed (Schultz/USAF); **(e)** Average DNL per person annoyed (Miedema).

<u>Discussion and Conclusions:</u>

The take-home messages from this analysis are:

1. **Separation Effects:** Figure 11a, Figure 12a, and Figure 13a show that for a range of base DNL values from 50 to 60 dBA, the average DNL for profile subpeak maxima reaches a minimum value with a subroute separation D ~ 2h – i.e., there is no gain by using larger separations between subroutes. This minimum DNL value approximates the physical 1/N reduction from spreading the overflights over N subroutes. This simply means that at a separation of at least 2h, the individual subpeaks no longer feed strongly into each other. This effect is dependent on the atmospheric attenuation parameter used in the calculation. We have used a noise *power* attenuation factor (0.04 %/ft) that is typical of a temperate coastal region like Palo Alto (see Table 1 for the overall conditions of the data collection under consideration).
2. **Dose-Response Effects:** We have shown results for two different dose-response curves, labeled *Schultz/USAF* and *Miedema* in the above analyses. The relationship between these curves is discussed in detail in Appendix A (see Figure 15 and Figure 16). In summary, the historical *Schultz/USAF* curve is the current FAA standard, but it is out of date and extremely permissive in that almost all the accumulated modern noise annoyance survey data from around the world lie above this curve, i.e., the *Schultz/USAF* curve counts only those observers *least* likely to admit they are annoyed.[15] The Miedema curve on the other hand, is based on estimates of the *median* percent annoyed at given DNL values, and more accurately represents what the accumulated annoyance survey data tell us.
3. **Total Number of People Annoyed:** In terms of total number of people annoyed, the effects of dispersing aircraft noise by means of a herringbone approach model depend both on which dose-response curve is chosen and on the base DNL level (total noise to be dispersed). For relatively low base DNLs (i.e., 50 – 55 dBA in the analyses above), the FAA's Schultz/USAF curve fails to produce a benefit by this metric, and in fact shows an increase of about 40% in total number annoyed.[16]

   However, the Miedema dose-response model shows a *decrease* in total number annoyed with subroute separation (as much as 50%) for both base DNLs of 50 and 55 dBA.

   For the highest base DNL value analyzed (60 dBA), *both* the Schultz/USAF and Miedema curves show an increase in total number annoyed: about 71% for Schultz/USAF (from a base of 113.9 persons per route mile), and 29% for Miedema (from a base of 237.5 persons per route mile). The total number annoyed eventually declines again for both curves with increasing subroute separation (sooner for Miedema than Schultz/USAF) as the cross-feed between subroutes from the very high initial noise level is diminished.

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[15] Schultz, Theodore J, *Technical Background for Noise Abatement in HUD's Operating Programs*, Report No. 2005 R, Bolt Beranek and Newman Inc., 8 November 1971 (see this link). Even at that early date, Schultz states (on Page 138): *"The situation is even more extreme in the U.S... It is well known that serious public annoyance is prevalent long before official complaints are lodged. It is therefore obvious that these criteria* [TCR: DNL 65 dBA] *are not adequate for aircraft noise abatement in the long run, since they are deliberately permissive."*

[16] This is the basis of the rationale that has led the FAA to adopt a policy of using concentrated, narrow approach corridors, as opposed to spreading out the approach routes, e.g., in herringbone patterns.

This all suggests that by this metric, the herringbone dispersion is more effective up to a base DNL value somewhat above 55 dBA. This is appropriate to residential areas that are affected by NextGen route concentration, somewhat removed from final airport approach patterns.[17]

4. **Average DNL Level per Person Annoyed:** The main objective of dispersing aircraft noise is to reduce annoyance on the ground in residential areas affected by the NextGen concentration of traffic — not only in terms of the total number of people annoyed, but also (and perhaps more importantly) in terms of the net sound levels causing the annoyance. A metric that captures this effect (and which the FAA has apparently not used) is the amount of noise (DNL) per person annoyed. This metric is shown in subplots (d) and (e) of Figure 11 through Figure 13. For both dose-response models, there are uniformly significant noise reduction benefits from using a herringbone dispersal pattern — the amount depends on how many subroutes are used and their separation. In the plots above, we can see a maximum reduction of 2-5 dBA, which is significant.

   Again, we note that with a herringbone pattern, this reduction comes from reducing the *number of aircraft* flying over a given ground point, *not the intrinsic noise contributed by any individual aircraft* (such as would result from increasing altitude significantly or maximizing the non-powered and clean glide approach to the airport).

Generalizing These Calculations — How Much Geography does a Herringbone System Use?

A herringbone route configuration spreads the noise from aircraft overflights over a wider area to reduce the DNL level of the noise at any given observation point. The amount of DNL reduction, and the amount of ground space required to accommodate a herringbone pattern, is a function of the number of subroutes used and the separation distance between them. As mentioned in the discussion above, there is no gain by having larger separations between subroutes than **D = 2h** (see Figure 11a, Figure 12a, and Figure 13a).

Assuming a subroute separation of **D = 2h**, and a minimum detectable overflight DNL value of 45 dBA, we can compute the total width required for a herringbone pattern by finding where the DNL value of the DNL profile falls below 45 dBA (see Figure 5).

Figure 14 shows the results of these computations. Clearly it takes more ground space to adequately disperse the 60 dBA base DNL overflight than the lower base DNL cases. However, the amount of space required to reduce the noise level below a typical ambient background level in a suburban residential area is not much different than the dispersion area used by flight paths before GPS-based NextGen was implemented.

[17] For example, in the Palo Alto area where the noise data were measured for this study, the aircraft DNL averages about 53.5 dBA ±1.5 dBA over about 1.5 years.

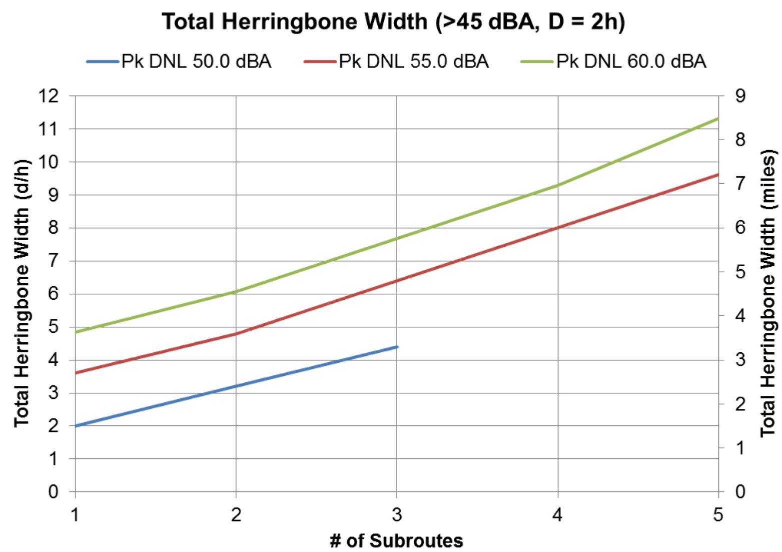

Figure 14: Overall widths of herringbone patterns as a function of the number of subroutes and base DNL. Curves are shown for base DNL values of 50 – 60 dBA. The left hand vertical axis shows the widths in **d/h** units, and the right hand vertical axis shows the widths in **miles** (assuming a 4,000 ft overflight elevation, such as seen in the north Palo Alto SERFR approach to the San Francisco airport, SFO). The curve for a base DNL of 50 dBA is truncated at 3 subroutes because the entire DNL profile falls below 45 dBA if more subroutes are used.

Appendix A

Aircraft Noise Dose-Response Curves

<u>Technical Considerations</u>

Given a measure of noise energy, e.g., DNL as is used extensively by the FAA, we would like to be able to infer what percentage of people exposed to a given noise level would find it annoying or otherwise harmful to their lives. This is called a dose-response curve — a noise level in produces a percentage out. In this paper, we developed DNL profiles across various herringbone subroute configurations, which indicate for each point on a profile the amount of noise people are exposed to. If we knew the population density at each profile point, we could calculate the number of people annoyed at each point and by integrating across the profile derive the total number of people affected.

This is, of course, a simplistic approach because different people have different sensitivities to noise. For example, different environments and background sounds make the same aircraft noise more or less noticeable. People doing different tasks (e.g., working, learning, problem solving, having a conversation, watching television, being in a stressful situation, sleeping, etc.) affects how disruptive noise is.

Researchers have nevertheless tried to come up with a simple dose-response relationship. One of the earliest and most influential efforts was the work of Theodore J. Schultz at Bolt, Beranek, and Newman in the early 1970s[18]. Using data from early studies of annoyance from aircraft noise (e.g., from the US, Europe, Australia, etc.), Schultz came up with a famous curve shown in two forms in Figure 15 that relates percent highly annoyed to DNL.

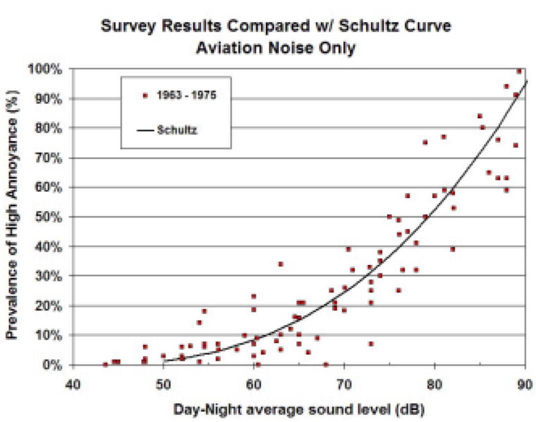

Figure 15a: Early 1978 version of the Schultz dose-response curve.

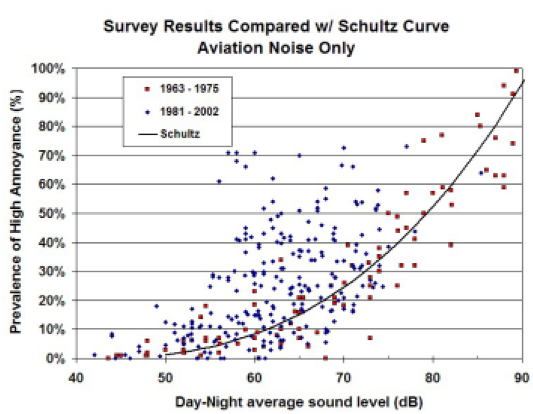

Figure 15b: 1978 Schultz curve with later survey data.

Figure 15: Two examples of the Schultz dose-response curve (a) superimposed on observer survey data as of 1975 (8a), and (b) on additional survey data as of 2002. (From the FAA Noise Effects Research Workshop, 4 March 2010)

In 1979 and 1980, Schultz's work, including his dose-response curve and the specification of the DNL 65 dB noise threshold "below which all land uses are deemed compatible", were incorporated into National Environmental Policy Act (NEPA).

[18] Schultz, Theodore J, *Technical Background for Noise Abatement in HUD's Operating Programs*, Report No. 2005 R, Bolt Beranek and Newman Inc., 8 November 1971 (see this link).

As seen in Figure 15, there was clearly a significant increase in survey data gathered between 1981 and 2002[19], many from studies outside the US. Many of the added annoyance results lie well above the earlier survey data Schultz used, i.e., more people were found to be annoyed by the same noise level. This suggests that over the more than 20 years following the 1978 curve, something happened to increase the sensitivity of observers, to increase the real ground noise level without increasing the DNL, or to improve the psychological methodology and statistics of the survey process.

The criterion of DNL 65 dB as a threshold for significant noise impact was established in 1980. At the 1992 Federal Interagency Committee On Noise (FICON)[20] earlier noise criteria were reviewed. The consensus reaffirmed DNL as the best noise exposure metric, endorsed the [Schultz] dose-response relationship to determine community noise impacts, and indicated broad acceptance of DNL 65 dB as a reasonable criterion.

The only minor change was the adoption of a new USAF (Armstrong Laboratory)[21] logistic (sigmoid) function to replace the previous polynomial representation of the Schultz curve for calculating the percent highly annoyed (%HA) in operational situations:

$$\%HA = 100/[1 + \exp(11.13 - 0.14\ L_{dn})] \qquad (A.1)$$

Even though considerable discussion has taken place since in scientific meetings on aircraft noise tolerance, the 1992 FICON meeting was the last in-depth review of these criteria by the FAA[22], despite growing evidence that the Schultz curve and the DNL 65 dB criteria are too permissive in authorizing ground noise levels that are very deleterious.

That being said, others have developed fits to the over 400 modern survey data sets now available on aircraft noise annoyance.[23] Figure 16 shows the data set points (a) and two fits to the data (b and c), one by Fidell (2011) and a comparison with another by Miedema and Vos (1998).

For the record, the functions describing the Fidell and Miedema fits are:

1. (Fidell) %HA = 100 exp(-A/m), where A = 110 and m = (10^(L_{dn}/10))^0.3 (A.2)
2. (Miedema) %HA = 0 if L_{dn} <= 42 dB

   (-0.2*(L_{dn} - 42)+0.0561*(L_{dn} - 42)^2)/100 (A.3)

[19] The 1978 data set used by Schultz included 160 survey studies. By 1993, there were 400 data sets available for assessment of the dose-response model.

[20] Federal Interagency Committee On Noise (FICON), 1992.

[21] Finegold LS, *U.S. Air Force research program on the effects of aircraft noise on humans: Current status and future directions*, in Proceedings of Noise & Man 1993, edited by M. Vallet ~L'Institut National de Recherche sur les Transports et leur Se´curite´, Arcueil, France, 1993, Vol. 2, pp. 229–231 July 1993.

[22] FAA Noise Effects Research Workshop, 4 March 2010.

[23] See for example, (a) Miedema, H., and Vos, H., *Exposure-response relationships for transportation noise*, J. Acoust. Soc. Am. 104, 3432–3445 (1998); and (b) Fidell S, Mestrea V, et al., *A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure*, J. Acoust. Soc. Am. 130 (2), 791–806 (2011).

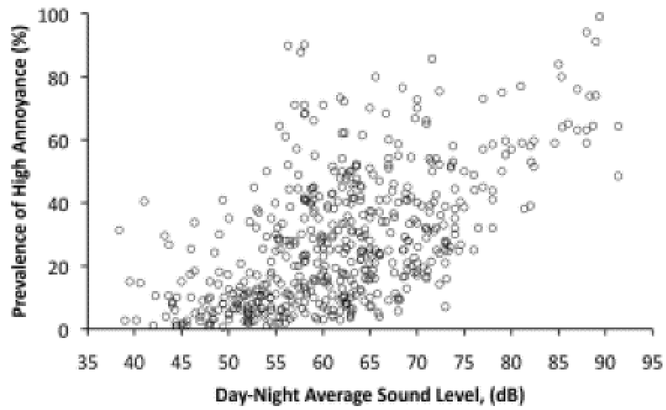

Figure 16a: Cumulative annoyance data sets as of 2011

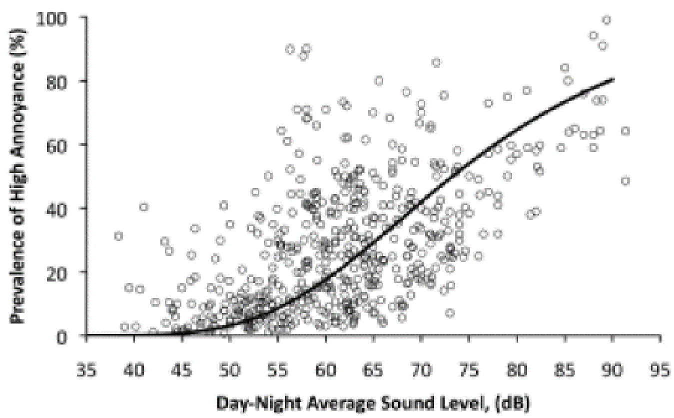

Figure 16b: Fidell fit to data

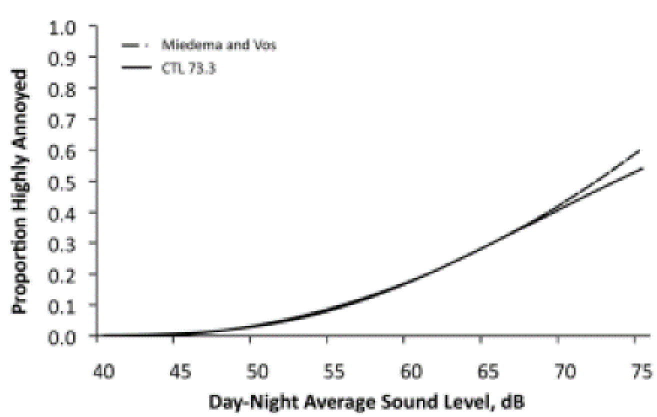

Figure 16b: Comparison of Fidell and Miedema fits to data.

Figure 16: Comparison of modern fits to available annoyance data sets as of 2011. (a) cumulative survey data; (b) fit of Fidell function to the data; (c) comparison of Meidema and Fidell fits. (from Fidell – see Footnote 23.)

It is instructive to compare Figure 15 with Figure 16, first to underscore the evolving quantity of sets of annoyance data (again mostly from studies outside the US). Second, the attempts to characterize the diverging swarm of annoyance data points with a single function seems increasingly untenable in terms of deriving meaningful policy decisions.

In Figure 16, the modern fits to the data are clearly more in line with what one would expect in minimizing squared errors across all the data (as compared to the obviously growing problems with the 1978 Schultz fit seen in Figure 15b). However, the overall variance in the data across the full range of DNL values (~20-40% annoyance units) remains very unsettling in terms of having an accurate predictive value for making a reasonable assessment of annoyance at any given exposure level.

The various curves are displayed for comparison in Figure 17. Basically, there are two approaches to fitting the data: (a) the established FAA model based on the Schultz/USAF curves, and (b) the more modern fits of the data based on the Fidell/Miedema curves (but not incorporated into FAA policy). For this analysis of the properties of the herringbone approach to noise reduction, we will estimate the number of people annoyed both with the Schultz/USAF and the Fidell/Miedema dose-response models.

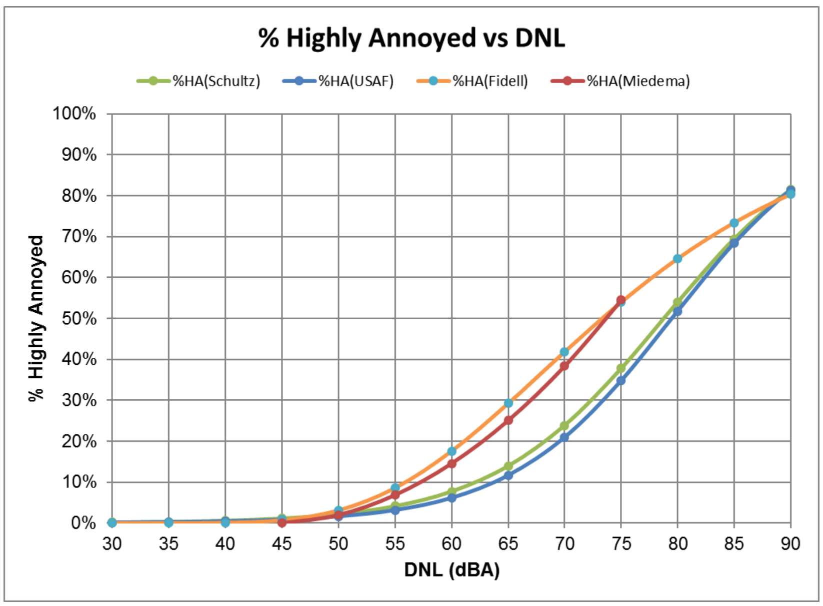

Figure 17: Comparison of the various approximations to annoyance survey data sets.